

Topology Control, Routing and the Better Transmission Path in Wireless Ad Hoc Networks

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ABSTRACT

In wireless ad hoc networks, different applications may have different requirements on data transfer which are not limited to being energy-efficient. Even in a single application, there may be different requirements. However, the existing topology control and routing algorithms usually considered only one factor, which could not satisfy the various requirements. In this paper, we present algorithms to integrate multiple factors into topology control and routing. We also illustrate that topology control and routing should be considered together when multiple factors are taken into account. Simulation results show that topologies derived under our factor-integrated topology control algorithms can preserve more desirable transmission paths which can be found by the factor-integrated routing algorithms.

Keywords: Wireless ad hoc network, topology control, power consumption, routing, transmission path.

1. INTRODUCTION

A wireless ad hoc network that is formed by only a collection of wireless nodes does not have any fixed infrastructure. Due to the resource limitations (e.g. energy and bandwidth limitations) in such a network, a lot of research topics, for examples, topology control and routing, have been deeply studied during the past several years.

Topology control is implemented in wireless ad hoc networks mainly by controlling nodes' transmission power. It usually pursues a situation where nodes can communicate with each other (directly or through intermediate nodes) while the energy consumption is small enough. [1], [2], [3], [4], [5] are several typical topology control algorithms which have received considerable attention. Routing algorithm is used in the networks usually to find energy-efficient paths connecting each pair of nodes. AODV[6] and DSR[7] are two of the most remarkable routing algorithms which have been broadly used.

During the past years, topology control and routing were studied separately as two different topics. They even rarely appeared together in the same paper. However, if we consider the relationship between topology control and routing, we will find that routing is actually based on topology control. This is because each node on a path should transfer messages using a transmission power which is determined by topology control. Without topology control, each node uses maximal power to send messages, which not only wastes energy, but may lead to interference augment and network throughput reduction. Therefore, topology control and routing should be studied together.

Although the past algorithms considered topology control or routing separately, all routing algorithms can still work properly with topology control algorithms if each node has all radio-covered nodes as its neighbors in the final topology. We call these topology control algorithms covered-neighbor based topology control(CNTC). (We will explain below that the existing routing algorithms cannot work with non-CNTC topology control.) Although CNTC includes almost all existing topology control algorithms, unfortunately it cannot meet various topology control requirements. This is because in CNTC, only energy-efficiency or something related, e.g. network interference, is mainly considered, while other factors are underrated or even ignored completely. However, topology control should consider more factors, for examples, node mobility and residual energy. Compared with a far but stable neighbor, a nearby neighbor moving frequently is usually not a good choice for the next hop since inconstant node will make a route unavailable quickly while finding a new route leads to network overhead. It is obviously true that multiple-factor consideration will make a topology as well as a route more applicable. However, few work has been done in this regard by now.

In this paper, we provide solutions and try to integrate multiple factors into topology control and route finding. We call them factor-integrated topology control(FITC) and factor-integrated routing(FIR) respectively. Note that CNTC has all radio-covered nodes as its neighbors in the final topology. However, this is not true for FITC since it needs to take into account more than one factor besides power consumption. Accordingly, this may make FITC select, for example, farther but more stable nodes as neighbors in the final topology, while leaving some radio-covered nodes unselected. Since the existing routing algorithms select next hop from all radio-covered neighbors, they cannot work properly with our new FITC algorithms. Therefore, we also discuss how to design factor-integrated routing(FIR) algorithms based on FITC.

This paper is an extension of our research on multiple-factor-considering topology control. In [8], we presented IALMST and IBEC topology control algorithms, both of which take energy-efficiency and interference into account. In [9], we presented LSP algorithm which determines the final topology according to link weight which can be derived from the power consumptions of the message sender, receiver and overhearers. We also presented our enhanced LSP algorithm named RLSP[10]. However, what were considered in these algorithms were limited to energy-efficiency and interference. In this paper, we will

present two topology control algorithms which can integrate most quantifiable factors. We also show how to quantify several typical factors usually concerned in wireless ad hoc networks. Based on the algorithms, we then discuss the design of routing algorithms. Simulation results show that these algorithms are effective.

2. PRELIMINARIES

To facilitate our discussion, we first define the following terms. We model the topology of a wireless network with each node using its maximal transmission power as an undirected graph $G = (V, E)$ in the two dimensional plane, where $V = \{v_1, v_2, \dots, v_n\}$ is the set of nodes in the network and E is the set of *bidirectional* links. Note that the network discussed here may be heterogeneous, and hence each node v_i may have its own transmission power p_i^t which can be adjusted by itself. However, since asymmetric communication is impractical in wireless multihop networks[11], in this paper, only bidirectional links are concerned. Therefore, the bidirectional link $(v_i, v_j) \in E$ implies that both v_i and v_j are covered by each other. We define the *physical neighbor set* N_i^p of each node v_i as

$$N_i^p = \{v_k | (v_i, v_k) \in E(G) \text{ or } (v_k, v_i) \in E(G)\}. \quad (1)$$

Therefore, topology control algorithm is actually a rule by which each node v_i selects its neighbors in the final topology from N_i^p . We call the neighbor *logical neighbor*. Note that the logical neighbor set N_i^l is a subset of N_i^p .

In our topology control algorithms, each link $(v_i, v_j) \in E$ is associated with a link quality vector $Q_{i,j} = (q_1^{i,j}, q_2^{i,j}, \dots, q_n^{i,j})$ where $q_k^{i,j}$ ($1 \leq k \leq n$) stands for the value of a quantifiable factor f_k . In the following we list several key factors mostly concerned in wireless ad hoc networks, and discuss how to quantify them and derive their values.

A. Minimal power consumption for supporting a link at sender(MPC)

This factor has been broadly considered in the existing topology control. However, different energy models have different definitions for it, and usually it is simply considered as the transmission power, which is impractical. We assume that at any time each node in the network operates in one of the following states: *Idle*, *Transmitting* and *Receiving*. Denote the power consumption at v_i in the three states as p_i^{idl} , p_i^{tx} and p_i^{rx} respectively. The p_i^{tx} can be broken down into two parts, i.e. the power consumed by RF amplifier p_i^{amp} and the one by non-amplifier p_i^{elec} . Denote the power efficiency of RF amplifier as η_i , then $p_i^{amp} = p_i^t / \eta_i$ where p_i^t is the transmission power. Thus the power consumed at the sender v_i is

$$p_i^{tx} = p_i^{elec} + p_i^t / \eta_i \quad (2)$$

The minimal transmission power $p_i^t(j)$ for supporting a link (v_i, v_j) is assumed to be

$$p_i^t(j) = p_j^s \times |v_i, v_j|^\alpha \quad (3)$$

where p_j^s is the receiver sensitivity of v_j , and α is the path loss exponent whose value depends on network environment. Therefore, the MPC $p_i^{tx}(j)$ can be given by

$$p_i^{tx}(j) = p_i^{elec} + p_j^s \times |v_i, v_j|^\alpha / \eta_i \quad (4)$$

For each node v_i , p_i^{elec} and η_i can be predefined since they are related to v_i itself. For each neighbor $v_j \in N_i^p$, p_j^s can be

derived at v_i through one-hop information exchange. We also assume that each node is capable of computing the distance from where a received message is sent by using GPS or simply according to the message's signal strength. Accordingly, for each node v_i and its neighbor $v_j \in N_i^p$, the MPC $p_i^{tx}(j)$ can be derived through one-hop message exchange.

B. Residual energy(RE)

RE is an important node property indicating residual network/route lifetime, and it is also a metric usually used to judge network load balance. However, it has been considered too little in topology control. In this paper, we consider it as an important factor for topology control. It is practical that each node v_i can detect its battery RE and meanwhile, through one-hop broadcasting, it can be known by each neighbor $v_j \in N_i^p$.

C. Node mobility(NM)

NM can be quantified by using node velocity. If a node has GPS support, it can get its position constantly, and hence derive its velocity. NM also can be quantified by using the amount of changed neighbors per fixed interval. The changed neighbors include new coming and recently left neighbors. While the first method needs GPS support, the second needs only a beacon mechanism.

3. FACTOR-INTEGRATED TOPOLOGY CONTROL

We now assume that each node v_i derives link quality $Q_{i,j}$ for each neighbor $v_j \in N_i^p$. Then we provide two algorithms to compute the final network topology.

A. Factor condition based FITC algorithm(FC-FITC)

FC-FITC predefines requirement for the network topology control which can be represented as $R = (r_1, r_2, \dots, r_n)$, where r_k ($1 \leq k \leq n$) is the requirement for factor f_k . Each r_k is a two-tuple (opt_k, val_k) where opt_k is a comparative operator which can be '<' or '>', and val_k is the value boundary for factor f_k .

Therefore, for node v_i with its neighbor v_j , if each $q_k^{i,j}$ in $Q_{i,j}$ is within the boundary of r_k , that is, if the inequation $q_k^{i,j} 'opt_k' val_k$ is satisfied, then v_i selects v_j as its logical neighbor in the final topology. To avoid unidirectional link in the final topology, if v_i is not selected by v_j as its logical neighbor, v_j will be deleted from N_i^l . This can be implemented through information exchange.

After deriving all logical neighbors from N_i^p , v_i can adjust its transmission power to just cover the most remote logical neighbor according to Eq. (3). Note that a node covered by v_i is not always a logical neighbor here since it may not satisfy the requirements of node mobility or residual energy.

Note that since we can define different requirements R according to different network types, FC-FITC is flexible and can satisfy topology control requirements in lots of networks.

B. Factor rating based FITC algorithm(FR-FITC)

In FR-FITC, we assign a link weight to each unidirectional link (v_i, v_j) according to $Q_{i,j}$. Since different factors cannot be simply integrated into a scalar quantity, they should be normalized first. There may be lots of normalization methods. Following is an example. We assume that in a network, each factor has predefined minimal and maximal values and let $Q^m = (q_1^m, q_2^m, \dots, q_n^m)$ and $q_k^m = (val_k^{min}, val_k^{max})$ where

val_k^{min} and val_k^{max} are the minimal and maximal values for f_k respectively. Note that factors may be 'good' or 'bad' for topology control and routing. For examples, RE is 'good' since a large RE value implies that the node can run for a long time, while NM is 'bad' since a large NM value means the path is not stable. For each 'good' factor f_x with value $q_x^{i,j}$, we define its factor weight $fw_x^{i,j} = (v_x^{max} - q_x^{i,j}) / (v_x^{max} - v_x^{min})$, and for each 'bad' factor f_y with value $q_y^{i,j}$, we define its factor weight $fw_y^{i,j} = (q_y^{i,j} - v_y^{min}) / (v_y^{max} - v_y^{min})$. FR-FITC predefines a vector $\Lambda = (\lambda_1, \lambda_2, \dots, \lambda_n)$ to rate each factor, where $\sum_{k=1}^n \lambda_k = 1$. Therefore, the link weight $w_{i,j}$ is given by

$$w_{i,j} = \sum_{k=1}^n fw_k^{i,j} \times \lambda_k \quad (5)$$

After deriving link weights, the network computes topology by using any link-weight-based topology control algorithm. LSP[9] is such an algorithm which only needs local (or one-hop neighbors) information but can preserve all global shortest paths in the final topology. For the sake of completeness, we list the main steps of LSP as follows.

- 1) Each node v_i exchanges the information of link weights with each neighbor $v_j \in N_i^P$. Therefore, for any two nodes $v_x, v_y \in N_i^P \cup \{v_i\}$, if there is a link, v_i can derive its weight $w_{x,y}$.
- 2) For each bidirectional link (v_x, v_y) , v_i can derive both $w_{x,y}$ and $w_{y,x}$ in Step a). Then v_i calculates the average link weight $\bar{w}_{x,y} = (w_{x,y} + w_{y,x}) / 2$.
- 3) Each node v_i computes the local shortest path connecting it to every neighbor $v_j \in N_i^P$ according to the derived average link weights. (Unidirectional link is not considered in LSP.) Denote the local shortest path as

$$path_{i,j} = (v_{p_0^{i,j}} = v_i, v_{p_1^{i,j}}, \dots, v_{p_{n-1}^{i,j}}, v_{p_n^{i,j}} = v_j) \quad (6)$$

where $v_{p_m^{i,j}} \in N_i^P$ and $m = 1, 2, \dots, n$. Then the logical neighbor set N_i^l can be represented by

$$N_i^l = \{v_{p_1^{i,x}} | v_x \in N_i^P\}. \quad (7)$$

That is, all the second nodes on the paths compose the logical neighbor set.

- 4) Each node v_i adjusts its transmission power to just cover the most remote logical neighbor.

Note that actually both FC-FITC and FR-FITC are frameworks, that means any quantifiable factor can be integrated into them. In FR-FITC, we even have not defined an algorithm to compute the final topology. *What is most concerned in this paper is how to integrate multiple factors into topology control algorithm.*

Unlike most of the previous topology control algorithms, both FC-FITC and FR-FITC may lead to special network topologies in which some radio-covered neighbors are not logical neighbors. Note that this is a strongpoint of our algorithms that *energy-efficient is not the only consideration in topology control.*

Since a radio-covered neighbor does not have to be a logical neighbor in FC-FITC and FR-FITC topologies, each node should remember all logical neighbors after topology control. The impact on the existing routing algorithms is that they cannot simply broadcast protocol messages, instead they should use one-hop multicast. In the following we will discuss routing algorithms in FC-FITC and FR-FITC topologies.

4. FACTOR-INTEGRATED ROUTING

In this section, we discuss the design of the FIR algorithms under FC-FITC and FR-FITC.

A. Factor condition based FIR algorithm(FC-FIR)

In FC-FITC, each logical neighbor is selected according to the link quality requirement R . That means, all links in the final topology have met the topology control requirement. As we have discussed, if we modify the existing routing algorithms by using one-hop multicast instead of broadcast, most of them can be adopted. We take AODV[6] as an example.

In AODV, when a traffic source needs a route to a destination, it initiates a route discovery process by *broadcasting* a route request (RREQ) packet. Any node receiving this packet updates its information for the source node and set up backwards pointers to the source node in the route table. If the node is either the destination or an intermediate node with a valid route to the destination, it unicasts a route reply (RREP) packet back to the source. Otherwise, it *rebroadcasts* the RREQ. Duplicate copies of the RREQ packet received at any node are discarded. As the RREP propagates back to the source, nodes set up forward pointers to the destination, and thus a forward path to the destination is established.

In FC-FIR, the RREQ broadcast/rebroadcast should be replaced by one-hop multicast. When initiating a route discovery process, the source node multicasts a RREQ packet to its logical neighbors. If a receiver is either the destination or an intermediate node with a valid route to the destination, it unicasts a RREP packet back to the source. Otherwise, it multicasts the RREQ to its logical neighbors. Note that this kind of modification can be used for most of the existing routing algorithms.

Furthermore, FC-FIR can provide special transmission paths for different application requirements. Following is an example. To derive a steady download speed for multimedia application, node v_{src} wants a path to v_{dst} with all intermediate nodes moving slowly enough. So it multicasts the RREQ packet with a path requirement $PR = (-, -, \dots, (<, 0.1), \dots, -)$, where '-' denotes that there is no special requirement, and '(<, 0.1)' denotes that the velocity of any intermediate node should be less than 0.1m/s. Consequently, if there is such a path in the topology, it will be established. Or v_{src} has to relax its requirement on node velocity.

B. Link weight based FIR algorithm(LW-FIR)

We assume that LSP algorithm is employed in LW-FIR. Therefore, in the final topology, each node can derive a local route table which contains all shortest paths connecting the node to its neighbors.

Note that the above modified AODV for FC-FITC is also applicable in FR-FITC. However, since LSP preserves the global shortest paths, we then modify AODV to show how to derive those shortest paths. In the RREQ and RREP packets, an additional field records the weight of the current signal path. When a source multicasts a RREQ packet or a destination unicasts a RREP packet, the field is initialized to zero.

If a node receiving the RREQ packet is the destination, it unicasts a route reply (RREP) packet back to the source. If the node is an intermediate node with a valid route to the destination, it unicasts the RREP packet with the field initialized to the weight of the valid route.

If a node receives the RREQ packet for the first time, it refills the field with the last link's weight, and re-multicasts the packet to its logical neighbors. Meanwhile, it records the current field value. If a receiver has received the packet before, it checks if the field value in the packet plus the last link's weight is smaller than its recorded value. If so, the node refills the field with the smaller value, and records it. Then it re-multicasts the packet. Otherwise, the packet is discarded.

If a node receives the RREP packet, it refills the field with the sum of the original value in the packet and the last link's weight, and then unicasts the packet to the next-hop specified in the packet.

Any node receiving the RREQ or RREP packet creates or updates a route according to the original AODV protocol except that a valid route entry with the same sequence number as the RREQ or RREP packet is updated only because the path weight in the route entry is larger than the weight of the current path recorded in the packet.

Note that the source may receive multiple RREP packets, and a packet with the smallest path weight contains the global shortest-path information.

5. PERFORMANCE EVALUATION

In this section, we present several sets of simulation results to evaluate the effectiveness of our topology control algorithms. In the derived topologies, we also evaluate route energy-efficiency and usability. We mainly compare the performance of FC-FITC and FR-FITC with LMST⁻[2] and CBTC[1] since both algorithms are remarkable energy-efficient algorithms with good performances. Note that we compare only to the optimized CBTC algorithm with parameter $\alpha = 2\pi/3$. In our simulations, we adopted LSP algorithm in FR-FITC.

The performance metrics used in the study include

- **Transmission power**
After topology control, each node adjusts its transmission power to just cover its most remote logical neighbor. We use this metric to denote the average value of all nodes' adjusted transmission powers after topology control.
- **Path power consumption**
We use this metric to denote the power consumption (for unicast traffic) of the least-weighted path connecting two nodes (i.e. v_0 and v_1 in our simulations). It reflects the energy-efficiency of a path. Note that each node on a path can use the transmission power adjusted after topology control or the power just covering its next hop to send messages. We use *path power consumption(fixed)* for the first case, while simply using *path power consumption* for the second. Note that for a path $(v_0, v_1, \dots, v_n)$, the path power consumption is $\sum_{i=0}^{n-1} (p_i^{tx} + p_{i+1}^r)$.
- **Transferred packets before route break**
When transmitting, each node on the path is consuming its energy. When a node cannot afford to send messages, the path is broken. This metric can reflect the usability of a route. Like the metric of path power consumption, we use *transferred packets before route break(fixed)* when nodes use the transmission power adjusted after topology control.

In our simulations, we select MPC and RE as two factors concerned. For MPC, we use the energy model presented in Section 2-A, and the parameter settings are listed in Table I. As shown in the table, each node has p^{idl} randomly distributed

TABLE I
ENERGY MODEL PARAMETER SETTINGS

Parameter	Value	Parameter	Value
p^{idl}	20-80mW	p^s	10^{-8} - 10^{-7}
p^{rx} (ratio)	1.2-1.6	α	4
p^{elec} (ratio)	1.2-2.0	η	0.2-0.8

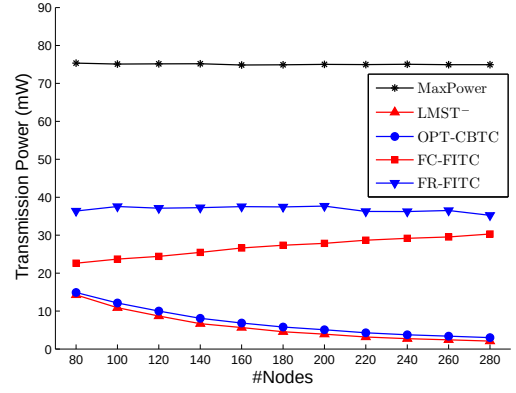


Fig. 2. The transmission power after topology control.

between 20 and 80mW. Its p^{rx} and p^{elec} are set to the ratios of the corresponding values to p^{idl} .

We define the topology requirement $R = ((<, 160), (>, 20000))$ (used in FC-FITC), the factors scope $Q^m = ((50, 250), (5000, 500000))$ and the factors rate $\Lambda = (0.5, 0.5)$ (used in FR-FITC). Note that in the three vectors, the former component is defined for MPC and the later for RE.

For a network with 100 nodes, the topologies derived using the maximal transmission power, LMST⁻[2], OPT-CBTC[1], FC-FITC and FR-FITC are shown in Figure 1. It is obvious that FC-FITC cannot preserve network connectivity which is determined by the topology requirement R .

Next we vary the number of nodes in the region from 80 to 280. Each data point is the average of 50 simulation runs. Figure 2 shows the average transmission power after topology control. Note that the transmission power in FC-FITC and FR-FITC are larger than in LMST⁻ and OPT-CBTC. However, this does not mean topologies under FC-FITC and FR-FITC consume more energy when transferring messages, which can be illustrated by the following results.

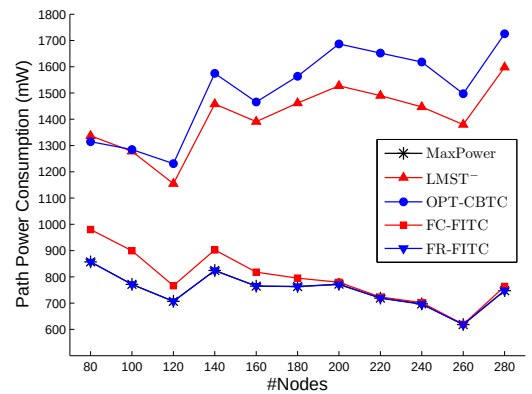


Fig. 3. Path power consumption.

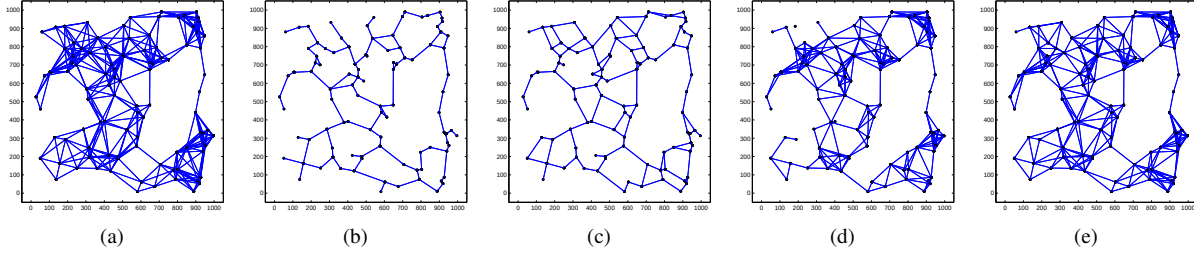


Fig. 1. Network topologies derived under different algorithms.(a)MaxPower. (b)LMST-. (c)OPT-CBTC. (d)FC-FITC. (e)FR-FITC.

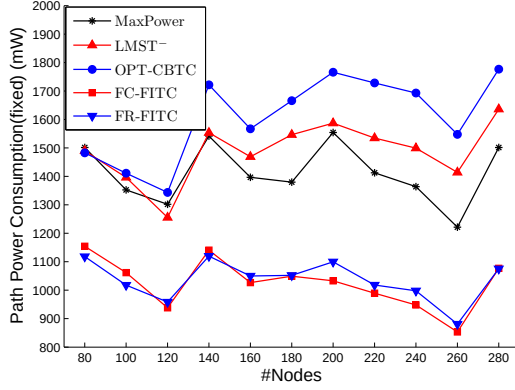


Fig. 4. Path power consumption(fixed).

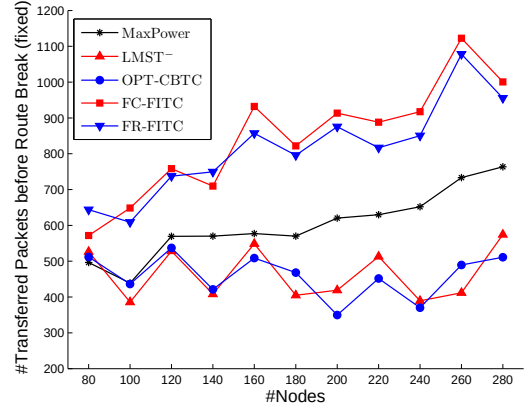


Fig. 6. Transferred packets before route break(fixed).

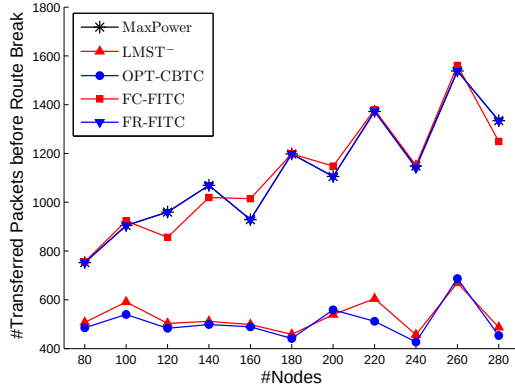


Fig. 5. Transferred packets before route break.

As we can see in figure 3, FC-FITC and FR-FITC outperforms LMST- and OPT-CBTC. Since FR-FITC uses LSP, it preserves the global shortest paths. That is why it has the same data as MaxPower. Figure 4 shows that the advantage of our algorithms is still obvious when nodes use fixed transmission power adjusted after topology control. Note that in our simulations the networks are heterogeneous, and the receiver also consumes energy, which may make long link more energy-efficient than shorter one. That is why MaxPower is even better than LMST- and OPT-CBTC.

Figure 5 and figure 6 show the transferred packets before the path is broken. Both figures illustrate that FC-FITC and FR-FITC can support more packets to be transferred.

6. CONCLUSION

We have proposed several factor-integrated topology control and routing algorithms. Differently from other algorithms, our topology control algorithms can take multiple factors into consideration. Consequently, the derived topology can preserve more desirable paths which can be found by our factor-integrated routing algorithms. Since our algorithms are actually frameworks, which means they can be initialized by using any factors as its parameters, they can satisfy various requirements from different applications.

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